CHARACTERISATION OF SEQUENCE COMPONENTS OF ISLANDED MICROGRID WITH LOW FAULT CURRENT

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ABSTRACT

In this paper, an islanded microgrid (MG) with an inverter-based source (IBS) is analysed using sequence components for unbalanced fault conditions. The inverter based islanded MG exhibits a low fault current due to the current limitation of power electronic based sources. The design of the protection system for inverter based islanded MG is challenging since a conventional overcurrent protection system is not a viable option for low fault current conditions. The sequence component-based fault detection can be a viable option in this scenario. However, the evaluation of the sequence components in the condition of low fault current deviates from the conventional method. Conventionally, sequence component-based fault analyses are conducted based on a very high fault current assumption while ignoring phase current in the healthy phases. On contrary, as a result of the low fault current from IBSs, the comparative proportion of the current in the healthy phases is no longer negligible when compared to the fault current. Therefore, during the evaluation of the sequence components, the fact that there is only a moderate difference between the current of all (faulty and healthy) phases also needs to be considered. In this paper, the influence of the different unbalanced faults in an islanded MG with only IBS is analysed including a detailed investigation of sequence components. Thereafter, an intuitive conclusion is made based on the analysis to characterise the fault conditions.

INTRODUCTION

In the present power system scenario, renewable energy sources are becoming very common due to the intensified awareness of environmental issues. The increased integration of renewable-based distributed energy resources (DERs) like solar PV, wind energy, fuel cells, micro-turbines, and energy storage devices has resulted in the development of the concept of microgrids [1]. According to the International Council on Large Electrical Systems, "*Microgrids are electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded* " [2].

The notion of MG conveys a fresh dimension to the electrical power system by introducing self-healing and improved power quality by controlling loads and DERs, thus reducing carbon emissions due to higher penetration of renewable energy resources, and potentially reducing the implementation cost of distribution lines by using renewable DERs [3]. However, MGs, especially islanded MGs with inverter-based sources as DERs, bring many challenges along with their various advantages due to the unique physical characteristics such as low short circuit ratio, low inertia, shorter distance between generation and loads, etc. [4]. The intrinsic features of the MGs make designing a protection system a complex and challenging issue due to the bidirectional power flow and intermittent nature of renewable energy sources, resulting in varying levels of fault current contribution [1] [5].

The available fault current in a network is a critical factor in designing the protection scheme. The fault current contribution is significantly different for synchronous generators and inverter-based sources. The maximum available fault current from IBSs is not higher than 1.2 to 2 times of rated current [6]. On contrary, the synchronous generator can provide enormous fault current compared to IBSs, which can be 4 to 10 times higher. Adaptive protection systems have therefore been demonstrated as a promising technique for MG protection in several researches [7][8][9]. This system requires the capability of updating the protection curves of the relays in online with robust communication infrastructure.

Most literature about the protection design for MGs is mainly focused on the grid-connected mode. Since 100% renewable based networks are monopolising the focus from all over the world, the development of a reliable and efficient protection system is required. Compared to the grid-connected mode, the short circuit current level decreases even further when the network is operating as an islanded MG with only inverter-based DGs. Therefore, protection system design is even more challenging in the islanded mode of operation due to the low level of short circuit current and changing network topologies, and may result in a failure to trip during a fault event [1]. Therefore, challenges arise in selecting and designing the appropriate protective schemes for islanded MGs.

In [10], a fault detection technique has been proposed based on the sequence voltages for the islanded distribution system with only inverter-based sources. The percentage of the increment of negative and zero sequences as well as the percentage of the decrement of the positive sequence are defined as the fault detection parameters. However, since negative sequence presents in all unbalanced faults and zero sequence is present in all ground unbalanced faults, even an insignificant difference in the fault impedance can violate the increment and decrement percentage of sequence components and can violates the condition for fault detection. Therefore, in this paper instead of the magnitude of the sequence components, the unique angular relation between the sequence components for different faults is analysed. However, in a conventional power system, the sequence component analyses are conducted based the assumption of the synchronous generators' high fault current contribution characteristics. With the difference of fault current level, the characteristics are required to be reviewed and redefined. Although the presented methodology appears to be a promising approach for the protection system designing of inverter-based MG, further research also needs to be done in the context of complex MG with more diverse fault configurations.

The rest of the paper is arranged as: next section presents the difference of the fault current level for grid connected system and the inverter based islanded MG system. The sequence component analysis is demonstrated thereafter, followed by the characterisation of sequence components for low fault current condition of inverter based islanded MG, finally the conclusions of the paper is given.

SYSTEM WITH DIVERSE FAULT CURRENT

In this section, the difference in the system current is demonstrated for a fault with both high and low fault current levels. This demonstration is attained by implementing the same fault in two systems: First is the inverter based islanded MG shown in Figure 1; Second is the same system but supplied by the grid instead of IBS. The IBS provides 30kVA of capacity with 65A (rms) maximum fault current. It is a three-house system with a multiple earthed neutral system (MEN). The per phase load is 9kVA. In the second system, the IBS is replaced with a grid of 12kA fault current capacity which is connected to the system by a 11kV/0.433 kV transformer. The simulation is conducted in SimPower Systems of the MATLAB Simulink platform.

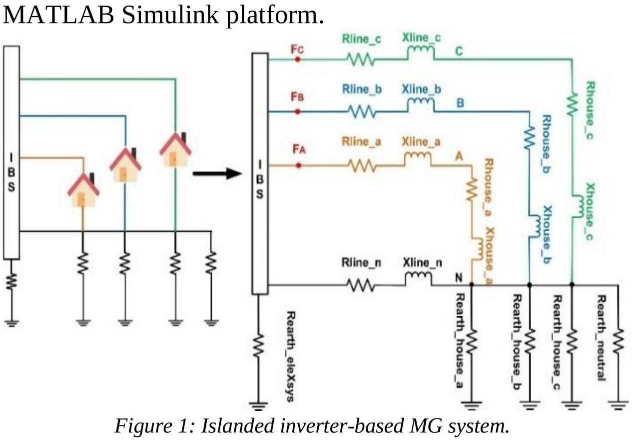

Figure 1: Islanded inverter-based MG system.

Phase A to ground fault (AG) of 0.01Ω resistance with a duration of 0.1s is applied at the point F of Figure 1 for both systems. In Figure 2 and 3, the current supplied by the grid and the IBS, respectively, are shown. From Figure 2, it can be observed that the available fault current for the grid connected system is about 840A. On contrary, for IBS supplied system, the maximum fault current is 91.92A which can be observed from Figure 3. The restricted allowable current flowing through power electronics devices to avoid thermal damage results the limited fault current contribution by IBSs. The low voltage fuses are typically sized to the nearest standard size above the circuit capacity. However, according to standard fuse curves, the operating time of the fuse is very slow for current twice the rating. Fault current needs to be 3 to 4 times the fuse rating (which is the continuous current carrying capacity) to operate in reasonably short time. Hence the use of conventional fuse protection is not a viable option for inverter based islanded MG.

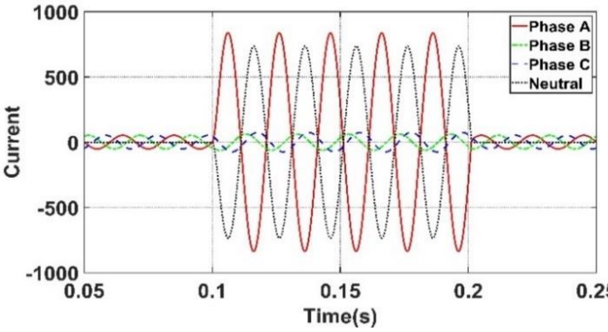

Figure 2: Three phase and neutral current from the grid for AG fault.

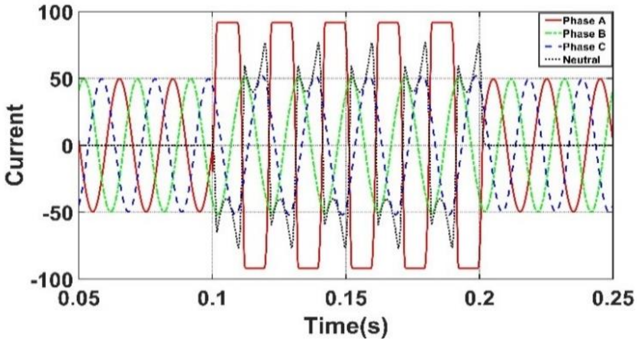

Figure 3: Three phase and neutral current from the IBS for AG fault.

SEQUENCE COMPONENT ANALYSIS

The sequence components are determined from phase components as follows:

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c) \quad (1)$$

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c) \quad (2)$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + aI_c) \quad (3)$$

Where I_a, I_b, I_c are phase currents, I_{a0}, I_{a1}, I_{a2} are sequence components, and operator $'a'$ represents $1\angle 120^0$. Conventionally, the current in the healthy phase is ignored and assumed zero while determining the sequence components due to the enormous fault current in the faulty phase compared to healthy phase. The different unbalanced faults have diverse characteristics with this assumption. Such as, for phase A to ground (AG) fault while considering $I_b = I_c = 0$, the positive, negative and zero sequence components are aligned with each other according to equation (1) to (3) as follows [11]:

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3} I_a \quad (4)$$

However, in the condition of low fault current, the current in the healthy phase is no longer insignificant. The sequence component determination process in this condition requires the consideration of the healthy phase current also. For considering load current I_b & I_c, there is no further simplification for sequence component equations (1) to (3). As a consequence, positive, negative and zero sequence components are not identical anymore for AG fault as:

$$I_{a0} \neq I_{a1} \neq I_{a2} \quad (5)$$

Similarly, for double phase (BC) fault and double phase to ground (BCG) fault, while considering $I_a = 0$ and high fault current flowing in faulty phases, the conditions are (6) and (7), respectively.

$$I_{a1} = -I_{a2} \quad (6)$$

$$I_{a1} = -(I_{a0} + I_{a2}) \quad (7)$$

Similarly, due to the consideration of load current through phase A, the conditions (6) and (7) for LL and LLG faults are not satisfied in low fault current condition. In a nutshell, it can be deduced that the sequence components are only determined based on the fault current for the high fault current condition. However, for the low fault current condition, the value of the sequence components will depend on the low fault current on the faulty phase as well as the load current on the healthy phase. The sequence components for the low fault current condition are determined and characterised in the next section.

CHARACTERISATION OF SEQUENCE COMPONENT

From the analyses of the previous sections, two key features are observed: firstly, the inverter based islanded MG exhibits a crucial difference in the fault current level compared to grid connected system, which makes the conventional overcurrent protection system an unviable option, and secondly the conventional relationship between the sequence components for different fault configurations diverges with the variation in the fault current level. Therefore, in this section, the inverter based islanded MG is examined with three types of unbalanced faults with both unloaded and loaded condition to demonstrate the deviated relations between sequence components for low fault current condition.

Phase to Ground

The same phase to ground fault which is applied in the Section II is also considered here. In order to demonstrate the difference between the sequence components when ignoring or considering the load current in healthy phase, both the unloaded and loaded conditions are investigated. The phase and neutral current for the no load condition are presented in Figure 4, and the vector representation of the corresponding current sequence components of phase A are presented in Figure 5. The faulted phase current is equal and opposite to the neutral current which can be observed in Figure 4. As no load current is flowing, the condition of equation (4) is satisfied and all sequence components (positive, negative, and zero) are equal as can be seen in Figure 5.

The phase and neutral current for the loaded condition is already presented in Figure 3. The significant difference between the sequence components for the loaded condition and unloaded condition can be observed from the vector diagram presented in Figure 6. There are differences in magnitude as well as in phase angle between sequences. The angular difference between positive sequence and both the negative and zero is same which is about 19°. These differences arise due to the considerable current in the healthy phases compared to faulted phase current. Therefore, to characterise the phase to ground fault in the case of inverter based islanded system, there are additional conditions: 1) reduced magnitude of negative and zero sequences; 2) angle difference between positive and negative sequences as well as between positive and zero sequences are need to be imposed.

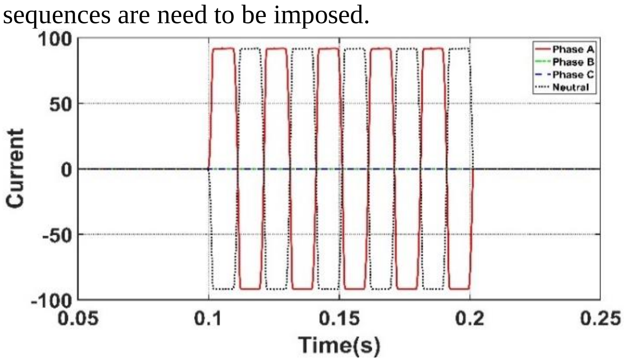

Figure 4: Three phase and neutral current supplied for no load condition with AG Fault.

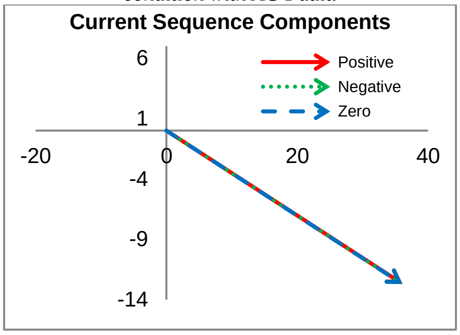

Figure 5: Vector diagram of current sequence components of phase A for no load condition with AG Fault.

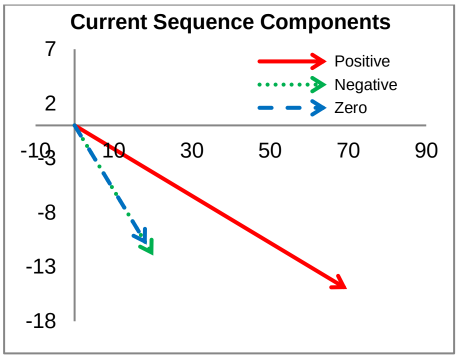

Figure 6: Vector diagram of current sequence components of phase A for full load condition with AG Fault.

Phase to Phase

A double phase fault between phase B and phase C is imposed at the same point F of Figure 1 for both unloaded and loaded condition. The phase and neutral current and the current sequence components of phase A for unloaded condition are given in Figure 7 and 8, respectively; and those signals for loaded condition are given in Figure 9 and 10, respectively. Since other phase has zero current, faulted phases have equal and opposite current. As a consequence, the characteristics of healthy phase of having opposing positive and negative sequence current, presented in equation (6), is justified which is demonstrated in Figure 8.

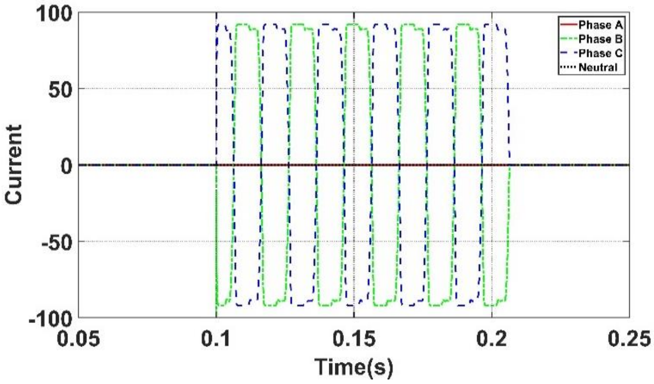

Figure 7: Three phase and neutral current supplied for no load condition with BC Fault.

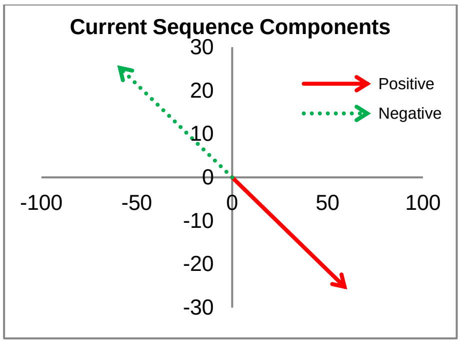

Figure 8: Vector diagram of current sequence components of phase A for no load condition with BC Fault.

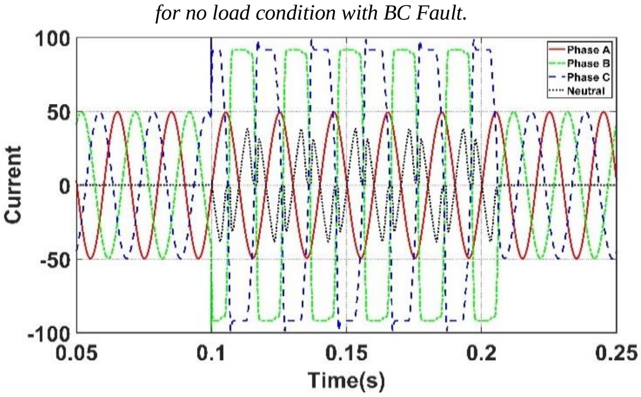

Figure 9: Three phase and neutral current supplied for full load condition with BC Fault.

Different characteristics in the phase and neutral current can be observed for loaded condition compared to the unloaded condition from Figure 9. As the phase A contains load current and also a strict limit is imposed on the current of fault phases, the system experiences a neutral current. Therefore, though the fault is only involved in phases, the zero sequence still exists that can be seen in Figure 10 and also the positive and negative sequences of phase A are not opposing as they are in the unloaded case. Therefore, to characterise the phase-to-phase fault in the case of inverter based islanded system, there are additional conditions: 1) zero sequence is present depending on the characteristics of the imposed current limitation; 2) the angular difference between the positive and negative sequences of the healthy phase is not 180° (171° in the considered system and fault configuration).

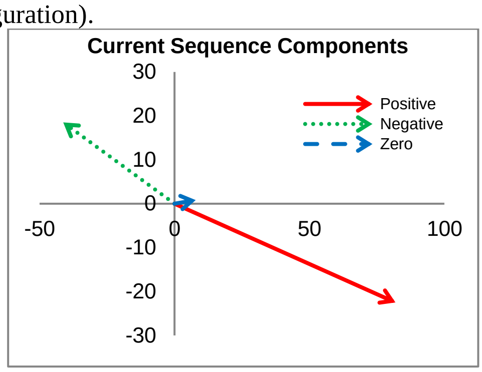

Figure 10: Vector diagram of current sequence components of phase A for full load condition with BC Fault.

Double Phase to Ground

The sequence components for unloaded and loaded conditions are analysed with a double phase to ground fault (BCG) here. With the ground involvement, there is significant current flowing through the neutral for the BCG fault which can be observed in Figure 11. As a consequence, from Figure 12, it can be observed that the zero sequence also presents along with positive and negative sequence currents as expected for double phase to ground fault. Moreover, the condition presented in equation (7) for the current sequence components of healthy phase during double phase to ground fault is also satisfied. For the loaded condition, the phase and neutral current and the sequence components of phase A are demonstrated in Figure 13 and 14, respectively. The neutral current is reduced for the loaded condition compared to unloaded condition due to the presence of load current in phase A.

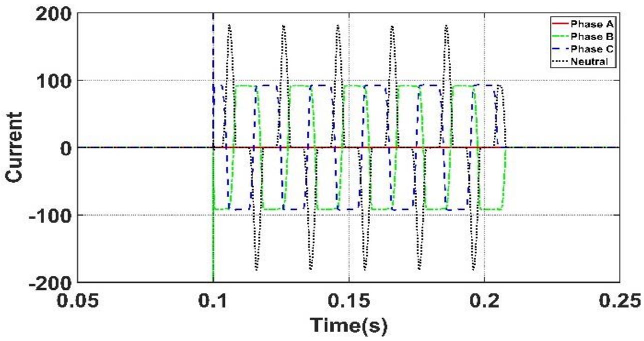

Figure 11: Three phase and neutral current supplied for no load condition with BCG Fault.

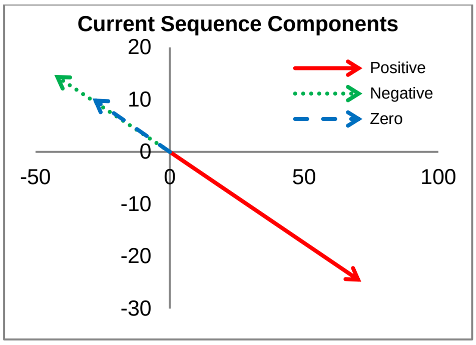

Figure 12: Vector diagram of current sequence components of phase A for no load condition with BCG Fault.

As a result of the presence of load current in phase A the condition of positive sequence being equal and opposite to the summation of negative and zero sequence is not satisfied anymore. This can be observed in Figure 14. Therefore, the characterisation of a double phase to ground fault can be summarised as: 1) reduced magnitude of negative and zero sequence currents; 2) the angular difference between the positive and negative sequence currents, and also between the positive and zero sequence currents of the healthy phase is not 180° (168° and 162.7°, respectively, in the considered system and fault configuration).

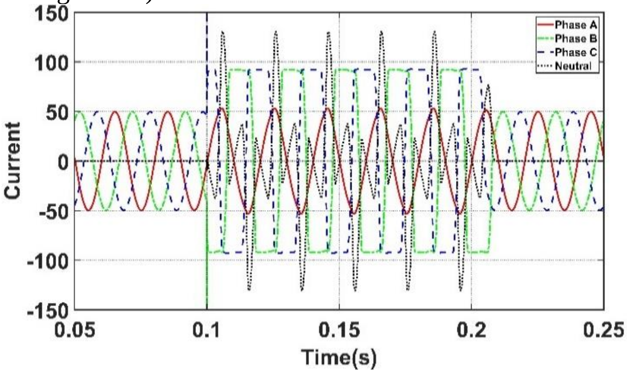

Figure 13: Three phase and neutral current supplied for full load condition with BCG Fault.

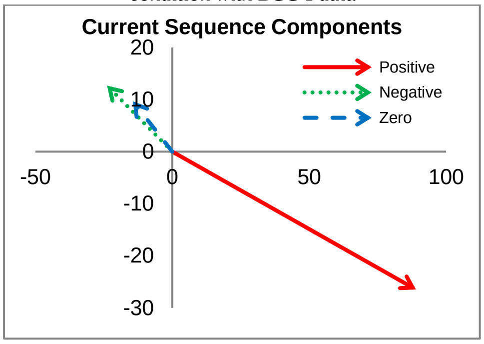

Figure 14:Vector diagram of current sequence components of phase A for full load condition with BCG Fault.

CONCLUSION

This paper demonstrates that inverter based islanded microgrids exhibit diverse features when compared with conventional grids. Therefore, further analyses is required to ensure the secure operation of inverter based islanded MGs with low fault current conditions. In this paper, at first, the unviability of the conventional overcurrent protection system for the islanded MG is demonstrated. Furthermore, the elemental difference between the inverter based islanded MGs and conventional grid for sequence-based fault analyses with different unbalanced faults is presented. Finally, the sequence current components are evaluated for unbalanced faults through simulation of the low fault current condition. It was observed that the characteristics of the evaluated sequence components deviate significantly from the characteristics of conventional grids. In a nutshell, the findings indicate that conventional sequence analyses require reassessment when considering the unique features of the inverter based islanded MG. This can indicate the direction for the design of protection systems using the sequence-based fault analysis.

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